IX ECCOMAS Thematic Conference on Smart Structures and Materials
SMART 2019
A. Benjeddou, N. Mechbal and J.F. Deü (Eds)

HIGH VOLTAGE SYNTHETIC INDUCTOR IN PIEZOELECTRIC SHUNT TO DAMP FLEXIBLE VIBRATING STRUCTURES

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Key words: Piezoelectric Shunt, Synthetic Inductor, High Voltage

Abstract. The use of resonant piezoelectric shunts is a well-established solution to mitigate vibrations in flexible mechanical structures. However, very large inductance values are required in the shunt. These values are difficult to obtain for passive inductors and therefore, inductance values are often synthesized with operational amplifiers (OpAmp). The downside is that standard OpAmps can only handle op to 30V peak-to-peak and the state of the art amplifiers up to 100Vpp. Piezoelectric materials typically generate high voltages even for low vibration levels. With the increasing push towards lighter and more slender mechanical structures, the increased vibration levels result in even higher voltage levels such that even the most advanced OpAmps fall short. In this research, a synthetic inductor is proposed and built by combining the bridge amplifier configuration and the output voltage boost configuration, effectively quadrupling the range of the synthetic inductor to 400Vpp. The synthetic inductor is then employed to shunt a piezoelectric patch bonded on a cantilever beam.

1 INTRODUCTION

Excessive vibrations in mechanical structures are typically reduced by adding another mechanical oscillator on the structure, called a tuned mass damper (TMD) [1]. With addition of a well-designed TMD, the vibrations are relocated from the original structure to this oscillator where they are dissipated, significantly decreasing vibrations in the mechanical structure. Piezoelectric (PE) materials can convert mechanical into electrical energy and vice versa. Therefore, bonding PE material to a vibrating structure and shunting it with a resonant electrical circuit will have the same effect as a TMD [2]. However, very large inductance values are required in the shunt such that resonance in the electrical shunt matches one [illegible]ctor coil with such a very large inductance and a low resistance at the same time. Therefore, this large inductance is often realized as a synthetic inductor. i.e., an active electronic circuit which mimics the electrical impedance of an inductor. A synthetic inductor consists of one or more operational amplifiers (OpAmps) and a number of passive resistors and capacitors. Another advantage of this approach is that the inductance can easily be made modified.

A well-known feature of piezoelectric material is its typically high-voltage and low-current operation. As OpAmps are limited in the voltage which they receive on their inputs, researchers have employed

”high voltage” OpAmps. The state-of-the-art high voltage OpAmps are the OPA445 (90V peak-to-peak) [3], used in many shunts which synthetize an inductor [4, 5], or more advanced, a negative capacitance [6] and more recentely digital impedance [7]. The OPA454 (100Vpp) is another high-voltage OpAmp with better specifications and an exposed metal pad for cooling the chip [8].

As mechanical structures nowadays tend to be more light and slender, the magnitude of vibration during resonance can reach levels that induce much higher voltages than 100Vpp in a PE patch. Similar concerns were raised in [9], were it was claimed a shunt was build which could handle 350 Vpp. However, the design of the circuit was not disclosed.

In the field of analogue electronics, several techniques are known to boost the output voltage range of an amplifier. The most straightforward technique is the “bridge amplifier configuration”, where two similar amplifiers are driven anti-phase. The load is connected between the two amplifier outputs, effectively doubling the output voltage range.

Another, less common technique is the “output voltage boost configuration”, where the positive and negative power supply voltages of the main amplifier are delivered by supply boost amplifiers. By selecting the proper boost amplifier supplies and gain factors it is possible to create a set of power supply voltages for the main amplifier, of which the average tracks the desired output signal, effectively doubling the output voltage range in an alternative way.

Employing a combination of both techniques, it is possible to quadruple the output voltage range. A new circuit has been designed and built, employing 6 high-voltage operational amplifiers, successfully synthesizing an inductor for a voltage range up to 400V. The circuit is tested experimentally as a shunt to mitigate the vibrations of a small flexible cantilever beam. The measured deflection of the beam under resonance with and without shunt confirms the expected mitigation even when the shunt is subjected to higher voltage levels than 100Vpp.

2 HIGH VOLTAGE SYNTHETIC INDUCTOR

2.1 High-voltage gyrator

The high-voltage synthetic inductor is built around a high-voltage gyrator of which the circuit diagram is shown in Fig. 1. This gyrator employs an OPA454 OpAmp, produced by Texas Instruments, which is to our knowledge the OpAmp with the highest voltage of operation commercially available. The OPA454 is specified at 100V (or +50V and -50V) supply voltage, with an absolute maximum rating of 120V.

The simulated input impedance is given by Ohm’s law as

$$Z_{in} = \frac{V_{in}}{I_{in}}$$

The OpAmp is configured as a voltage buffer, delivering an output voltage

$$V_{out} = V_{in} \cdot \frac{R}{R + \frac{1}{j\omega C}} = V_{in} \cdot \frac{j\omega RC}{1 + j\omega RC}$$

Hence the voltage drop across R_L is equal to the difference between the input voltage and the OpAmp’s output voltage. Therefore the current through R_L can be found from Ohm’s law. As the components are chosen in order to make $R_L \ll R$, the input current is approximately equal to the current through R_L:

$$I_{in} \approx \frac{V_{in} - V_{out}}{R_L} = \frac{V_{in} - V_{in} \cdot \frac{j\omega RC}{1+j\omega RC}}{R_L} = \frac{V_{in}}{R_L\,(1 + j\omega RC)}$$

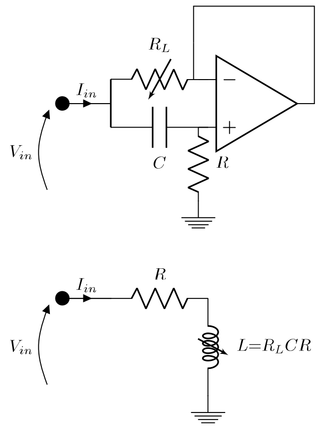

Figure 1: High-voltage gyrator with OPA454 OpAmp

The resulting simulated impedance is

$$Z_{in} = \frac{V_{in}}{I_{in}} \approx j\omega RC \cdot R_L + R_L$$

This means the gyrator simulates an inductor with a value of $C \cdot R \cdot R_L$ Henry, in series with a small resistor R_L.

If the gyrator circuit in employed as a shunt to attenuating mechanical vibrations with piezo transducers, a series resistor larger than R_L often required so the presence of R_L does not compromise the performance of the vibration damping. Therefore it is not necessary to employ gyrator circuits without series resistance but with a higher OpAmp component cost, such as the stanard Antoniou circuit, used in mant resonatn shunts [4, 5, 10].

2.2 Power supply boost configuration

It is possible to extend the voltage range of an amplifier by dynamically modifying the power supply voltages depending on the desired output voltage. The power supplies V_{pos} and V_{neg} of the central amplifier, used for the gyrator circuit, are now delivered by two similar OPA454 OpAmps, one supplied with a positive voltage and one with a negative voltage, referred to ground. By means of an equal-resistor voltage divider between the OpAmp's output and the positive or negative power supply voltage, followed by a voltage buffer, the supply boost OpAmps deliver

$$V_{pos} = \frac{V_{out} + 100V}{2}$$
$$V_{neg} = \frac{V_{out} - 100V}{2}$$

The principle is schematically drawn on Figure 2, where both left and right a gyrator is supplied this way.

Therefore the central amplifier's output voltage range is now extended to $200V_{pp}$ as the power supply voltages track the output voltage when referring to ground level, whereas the total supply voltage accross the central OpAmp always remains equal to

$$V_{supply} = V_{pos} - V_{neg} = 100V$$

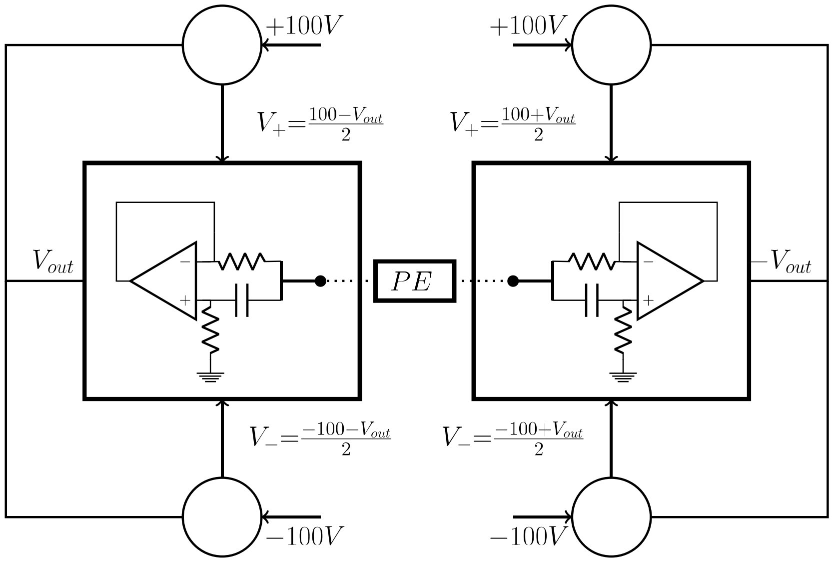

Figure 2: Extending the voltage range of a synthetic inductor with Power Supply Boost and Bridge configuration. Voltages determined based on antisymmetric excitation by the central piezo element PE.

The principle of operation is illustrated by means of the waveforms in Fig. 3. In this graph the power supply boosted gyrator is driven to its full output voltage range on a ±100V symmetric power supply.

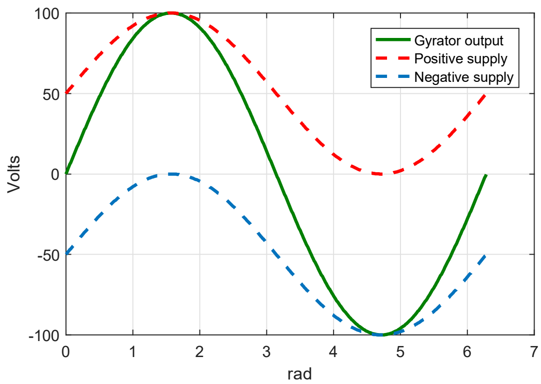

Figure 3: Power supply boost operation

2.3 Bridge configuration

The Bridge Tied Load (BTL) configuration is well-known in the field of amplifier design to be able to deliver an output amplitude which is twice the voltage range of an individual amplifier. To achieve this range extension, two amplifiers are driven antiphase and the load is connected between the two outputs. On Figure 2, the left and right gyrators are indeed driven antiphase, with the piezo element PE functioning as a source in between the two outputs, sourcing current in one terminal and sinking the same current from the other terminal.

This approach is used to provide a second doubling of the voltage range of the gyrator. Basicaly two simulated inductors with voltage boost configuration are employed in series, effectively quadrupling the output voltage range to $400V_{pp}$. Because the piezo transducer is connected between two gyrator outputs, the gyrators appear in series with respect to the piezo transducer, doubling also the simulated impedance. Using similar component values in both gyrator circuits, the resulting impedance is equal to

$$Z = 2j\omega C \cdot R \cdot R_L + 2R_L$$

Practical component values are $C = 1\mu F$, $R = 1M\Omega$ and $R_L = 100\Omega$, resulting in an inductance of 200H in series with a 200Ω resistor. In the implementation R is determined by a $1M\Omega$ potentiometer, allowing the inductor to be adjusted from 0 to 200H. On Figure 5a and Figure 5b show the experimentally contructed circuit.

3 ELECTROMECHANICAL SYSTEM

3.1 Theotical model and tuning

The vibrating mechanical structure of the experiment is a cantilever beam, bonded with 2 PE patches near its fixed end, as shown on Figure 4. The first PE patch will be used to excite the beam, while the other patch on the opposite side will be shunted by the RL shunt, synthesized by the circuit presented in the previous section.

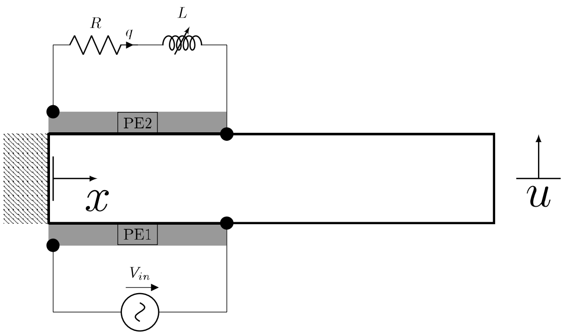

Figure 4: The considered dynamical system, a cantilever beam with PE1 used as an actuator and PE2 shunted with a RL shunt

By decomposing the dynamic deflection of the beam in a mode shape and a modal time coordinate $u(x,t) = \varphi(x)r(t)$, the dynamical equation of the full system can be written as [11]

$$\begin{cases} \ddot{r} + 2\zeta\omega_n\dot{r} + \omega_n^2 r - \theta_2 V_2 = \theta_1 V_{in} \\ C_{p,2}V_2 + \theta_2 r = q \end{cases} \tag{1}$$

with ω_n the short circuit natural frequency, ζ the modal damping, θ_1 and θ_2 the modal coupling coefficient of each PE patch and C_p the capacitance of the second PE patch. The equation (1) can be seen as a mechanical oscillator excited by the first piezo and an electrical interaction with the second piezo, depending on shunt circuit. When shunted by an RL shunt, $V_2 = -R\dot{q} - L\ddot{q}$, the R and L can be optimised in such a way that the vibrations at the resonance conditions of the mechanical oscillator are minimized, while also avoiding to create other significant resonances. In this research, the optimizing procedure is based on how mechanical TMD's are optimized [1], applied to resonant shunts [10]. The optimal electrical parameters are :

$$\omega_e = \omega_n \sqrt{1+k^2} \quad \zeta_e = \sqrt{\frac{3}{8}}k$$

with $\omega_e = \frac{1}{\sqrt{LC_{p,2}}}$ the electrical natural frequency, $\zeta_e = \frac{RC_{p,2}\omega_e}{2}$ the electrical damping and $k = \sqrt{\frac{\omega_n^2 - \omega_{n,CC}^2}{\omega_{n,CC}^2}}$ the effective coupling coefficient with $\omega_{n,SC}^2$ the resonance frequency of the mechanical oscillator when $V_2 = 0$, meaning when the second patch is shorted over its terminals.

3.2 Experiment

The optimization described above is very practical as only the open and closed-circuit resonances are needed, two parameters which are easily found experimentally.

A 166 *mm* long, 35 *mm* wide and 0.2 *mm* thick aluminum beam was fitted with two PIC255 piezoelectric patches which are 30 *mm* wide, 50 *mm* long and 0.2 *mm* thick and have a C_p of 103 *nF*. Further material constants are found on [12]. To identify the closed and open circuit resonances, a sine sweep with amplitude 100 *V* was applied to the actuating PE-patch with the other patch first in closed circuit, then open circuit, and finally with the optimized circuit. The deflection of the beam at the free end is measured with a laser vibrometer and both the applied voltage and measured deflection are used to construct an experimental frequency response function as shown on Figure 6a. The experimental open-circuit resonance frequency is 67.68 *Hz* and the closed 67.33 *Hz*. The generalized coupling coefficient is $k = 0.1021$ resulting in an optimal $R = 2.9k\Omega$ and $L = 54$ H. As expected, the FRF when using the shunting PE patch, seen on Figure 6a, shows a significant, almost 10-fold decrease of the vibrations near the resonance of the mechanical oscillator.

To verify the high voltage over the RL shunt during vibration damping, the open circuit resonance frequency is applied to PE1 as a 200Vpp sine wave, while the voltage over PE is measured, once in open circuit and once when the RL shunt is applied, Figure 6b. The synthetic inductor can easily handle the measured voltage over the shunt (178Vpp), which would not be possible with conventional OpAmps, or with a single high-voltage OpAmp. Note that the applied voltage, 100V, corresponds to only 7 mm amplitude at the tip of the beam, Figure 6a when PE2 is in open or closed circuit.

4 CONCLUSIONS

This research presented a high-voltage synthetic inductor consisting of 6 operational amplifiers, with an increased range from 100Vpp up to 400Vpp. This way, resonants shunts used to mitigate vibration of mechanical structures are able to deal with the increasingly high vibration levels which induce high voltages in these shunts. By supplying a single gyrator circuit by output voltage boost configuration, where the supply of operational amplifiers depend on their output, the voltage range of the gyrator was doubled. Another doubling was achieved by then supplying two of these gyrators in an anti-phase manner. The circuit was designed and used as a shunt for a piezoelectric patch bonded to a cantilever beam. The vibration in the beam induced voltages up to 178Vpp in the shunt, a voltage level where previous implementations of synthetic inductors are not able to deal with.

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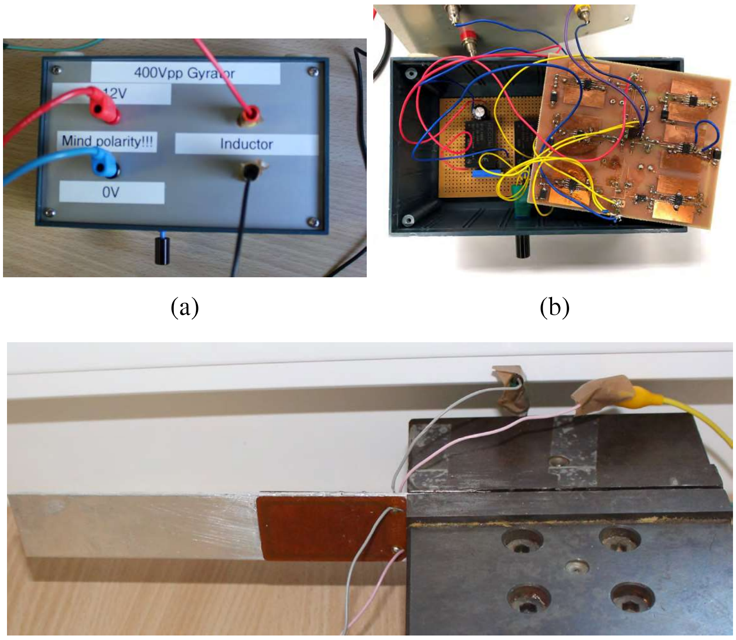
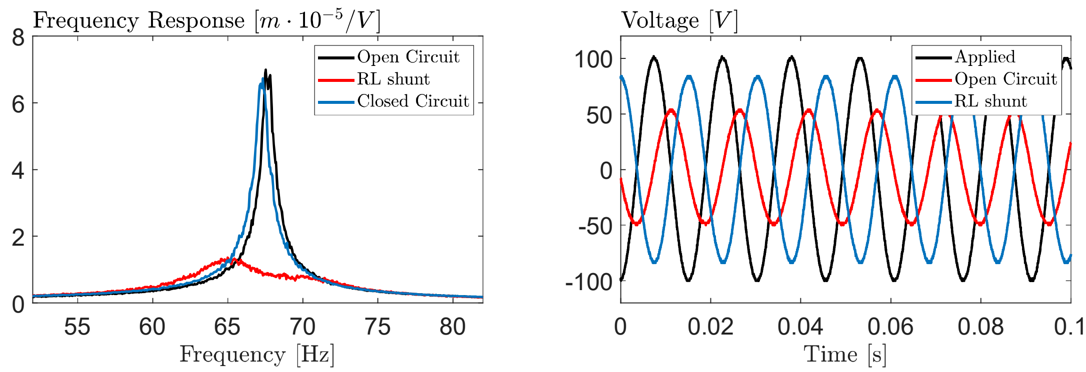


(a) (b)

(c)

Figure 5: The case of the 400Vpp synthetic inductor, closed (a) and open (b). The variable resistor is seen at the bottom center. The beam with PE patch bonded (c) on both sides.



(a) (b)

Figure 6: Frequency response function with PE2 open, closed circuit and shunted (a) and resonant voltage applied to PE1 and generated by PE2 (b).

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